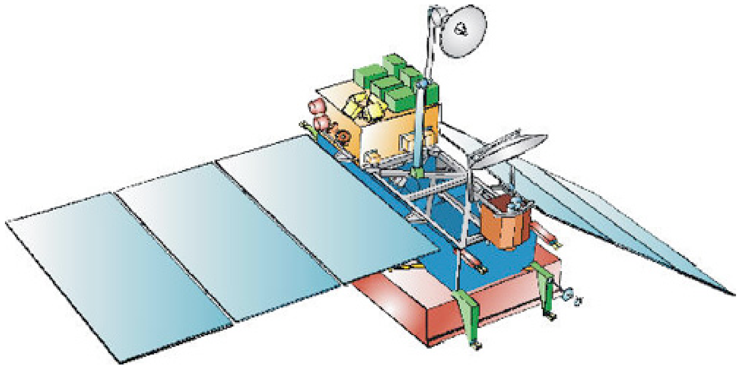
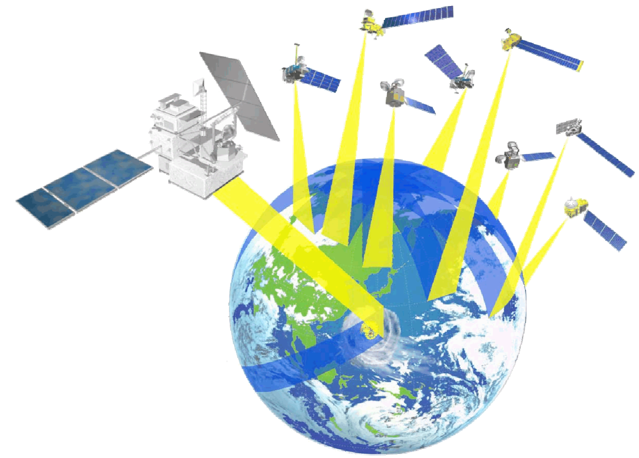




Precipitation Profiling Algorithm
(mostly issues)

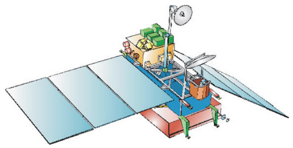
Toshio Iguchi (NICT)

7 November 2006

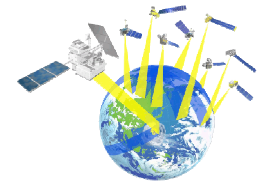
The 6th International GPM Planning Workshop (Annapolis, MD, USA)

Issues in TRMM/PR

- Uncertainty in DSD parameters (*Z-R*, *k-Z* relationships) = uncertainty in rain estimates
  - For light rain, constraint by SRT is weak.
  - SRT may be biased, especially over land.
  - Underestimation of RR over land
    - Correlated with thunder storm?
    - Algorithm itself?
- A storm model must be assumed.
  - Convective rain: snow, graupel, hail
  - CLW and WV profiles



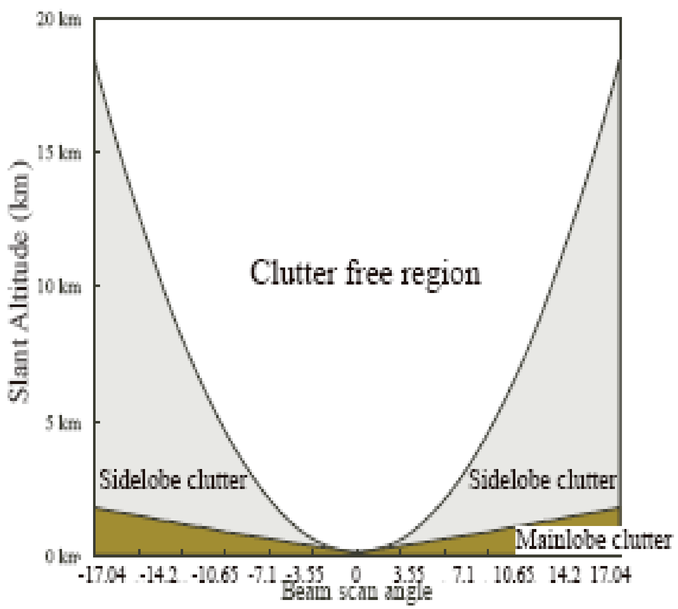
Improvements from PR we can expect with DPR

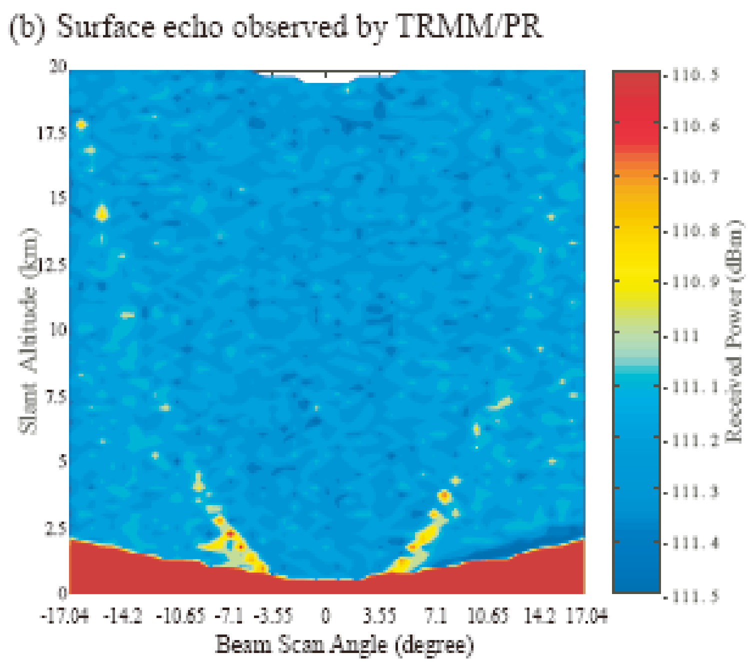


- Sensitivity
- Sampling intervals
  - Overlapped (interlaced) sampling in the along-track direction in the inner swath (KaPR)
  - Over-sampling in the range direction
    - 125 m when Δr=250 m (up to H=14 km)
    - 250 m when Δr=500 m (up to H=14 km)
- Guaranteed maximum measurement height
  - 19 km (TRMM/PR: 15 km)
- Accuracy of rain estimates
- Etc.

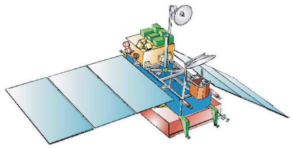
Issues insolvable with GPM/DPR

- Detection of rain very close to the surface
  - Rain with very low storm top will be missed
  - Rain profile near the surface must be assumed
- Etc.

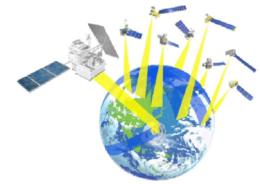




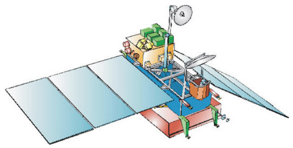
(figures by Dr. T. Tagawa)



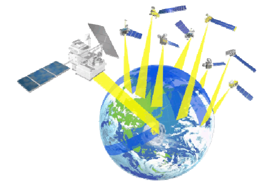
Roles of DPR in GPM



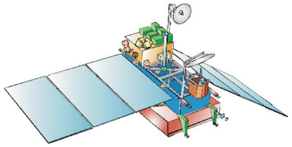
- To provide DSD information
  - Higher accuracy in rain rate estimates
  - TRMM PR algorithm uses a predefined DSD model (*Z-R* relationship) for light rain.
  - Increase in the accuracy of light rain estimates is essential in GPM, especially in high latitudes.
- To provide the phase-transition (freezing) height.
- To provide high resolution reflectivity data.
  - Δx=3.5 km (narrow swath), Δx=5 km (wide swath)
  - Sampling: Δr=125 m (up to H=14 km), Δr=250 m
  - Resolution: Δr=250 m (Ku, Ka), Δr=500 m (Ka, HS-mode)
- Both DSD and phase-transition height information is crucial to rain rate retrieval with MWR.



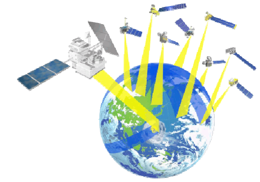
Questions and Challenges (1/5)



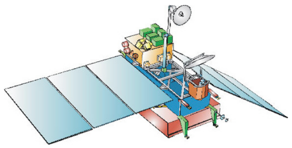
- How to combine Ka- and Ku-band reflectivity data to maximize the information extracted.
  - DPR algorithm development in realistic cases
    - Beam mismatching
    - NUBF effect (finite horizontal resolution)
    - Unknown attenuation due to CLW and WV
    - Unreliable SRT
    - Surface clutter
    - Unknown phase of precipitating particles
    - Finite range resolution
    - Fading noise in received signal
    - Fluctuating noise in received signal
    - Etc.



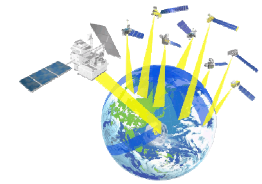
Questions and Challenges (2/5)



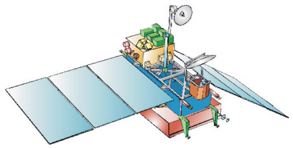
- Beam matching: Ka and Ku beams may not match 100%.
  - Up to 1 km difference in horizontal direction
  - Detection and quantification of beam mismatching
  - How serious is this difference?
  - How to compensate its effect in DPR algorithm?
- NUBF effect
  - How serious is the NUBF effect in the DSD retrieval algorithm?
  - Can we quantify it by using more densely sampled data (Δx=3.5 km (narrow swath)) than TRMM/PR? To what extent can we compensate it?



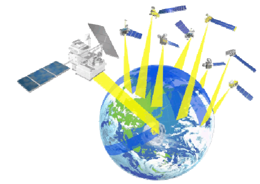
Questions and Challenges (3/5)

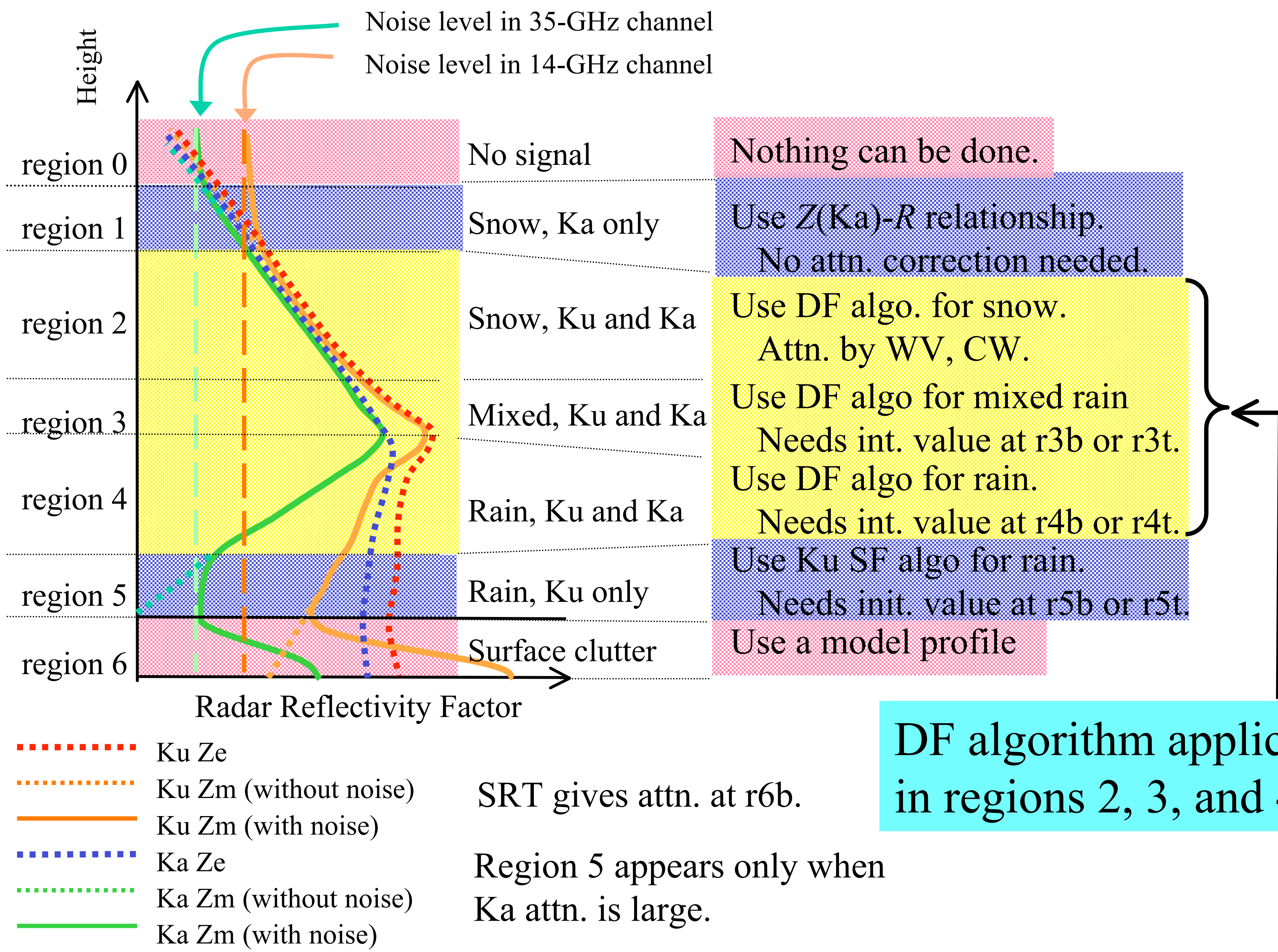


- Available information differs according to place, height, attenuation, incidence angle, surface conditions, etc.
  - The accuracy of estimates differs accordingly.
  - How to make no discontinuities in estimates between different cases statistically.
- Region where the DF algorithm is applicable.
  - How to use the detailed information in this region to its vicinity.



Applicable Range of DF Algorithm

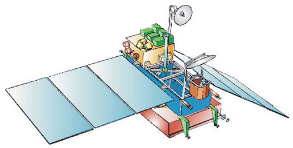




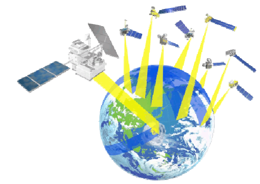
SRT gives attn. at r6b.

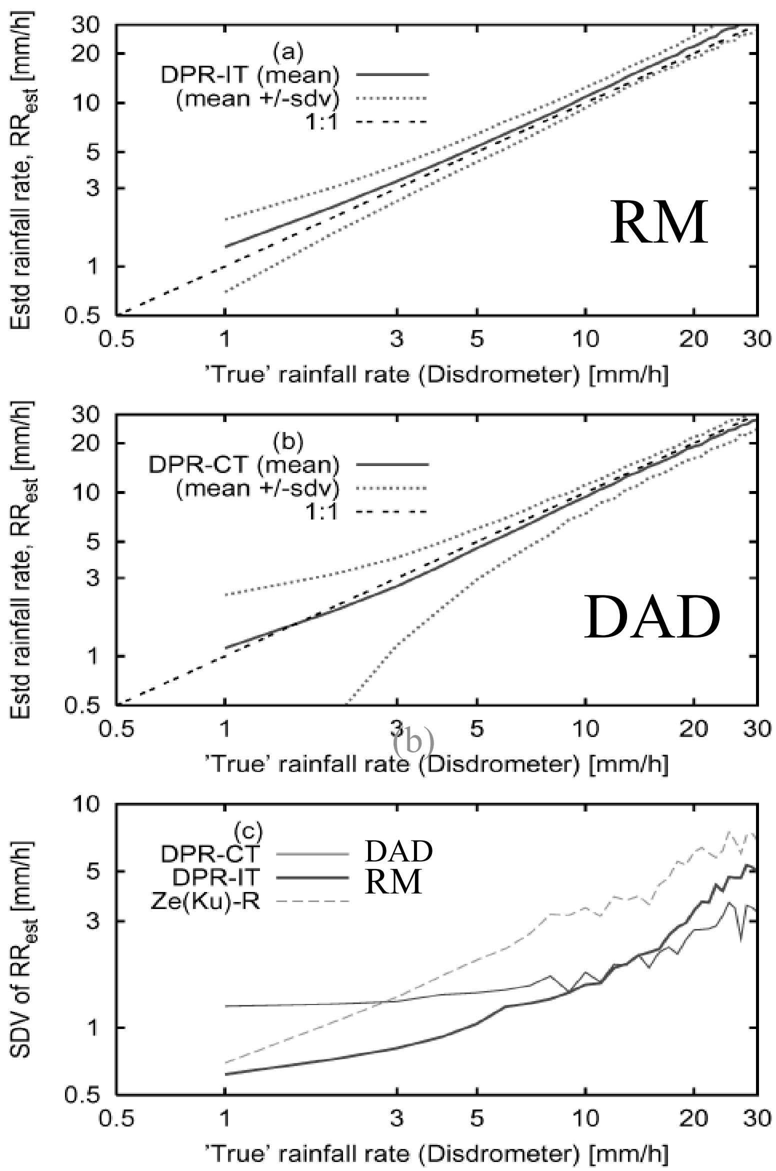
Region 5 appears only when Ka attn. is large.

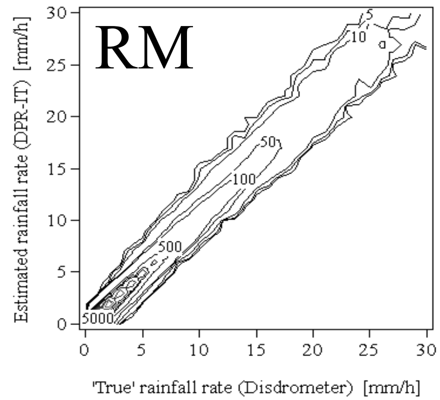
DF algorithm applicable in regions 2, 3, and 4.



Errors from different algorithms

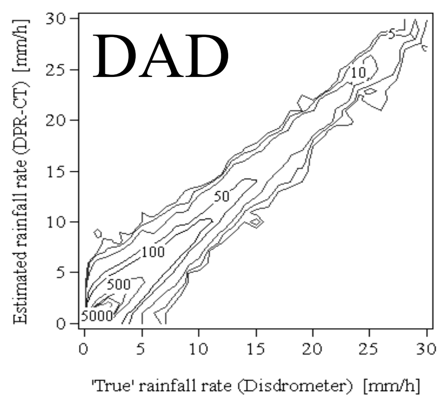


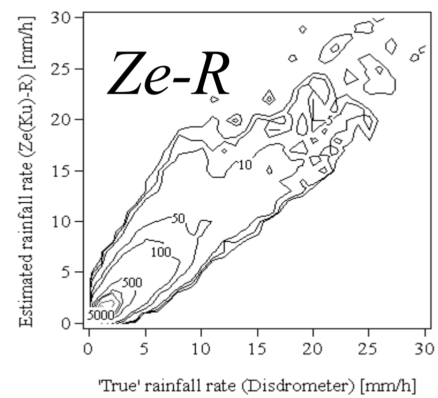




RM: Meneghini's DF method

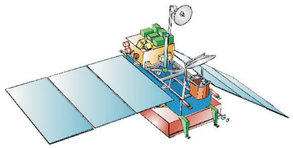
DAD: difference of att. difference



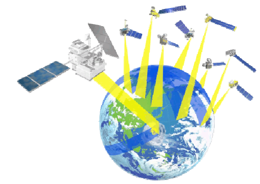


Disdrometer-measured DSD derived 'true' rainfall rate versus algorithm- (a) DPR-IT, (b) DPR-CT and (c) *Ze*(13.6 GHz) - *R* derived rainfall rate averaged over 3 km rain-path. The contours represent the 2D-histrogram of the retrieved rainfall rate calculated at each channel of 1.0×1.0 mm h^{-1} of the true and the retrieved rainfall rates.

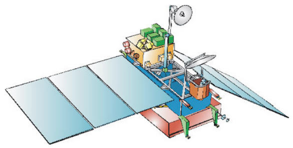
(by N. Adhikari)



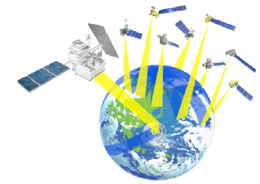
Questions and Challenges (4/5)



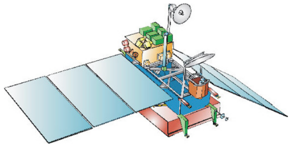
- How to combine different kinds of information in different cases is a challenging issue.
  - E.g., CLW, WV profiles, Snow density, MWR data, Vicinity data
  - E.g., Attenuation due to CLW and WV
    - Attenuation, especially of Ka signal, due to CLW and WV may become sources of error.
    - If DSD information is accurately estimated by a DF algorithm and if SRT is reliable, it may be possible to estimate the attenuation due to CLW and WV (provided that there is no NUBF effect).



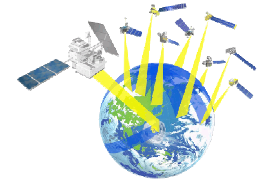
Questions and Challenges (5/5)



- To what extent can we improve the estimates?
  - In terms of
    - rainfall rate
    - Other parameters:Snowfall rate, Storm height, Storm area, Storm structure, Surface conditions, etc. (CLW, WV?)
  - Distinction between rain, snow, graupel, and hail
  - DSD parameter estimation



A possible DPR L2 algorithm flow



$Z_m(r;\mathrm{Ka})$
$Z_m(r;\mathrm{Ku})$

↓

Precipitation Type (PT) = $PT_1,\ldots,PT_n$

SRT, CLW, WV, beam mismatch, Surf. T, etc. →

Prior knowledge

← Characteristics of each PT

↓

Retrieve precipitation profile assuming $PT=PT_i$

Residual errors in PIA, Deviation from typical DSD, etc.

← PDF of typical profiles in each PT

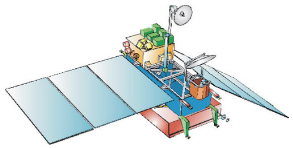
↓

Choose the most likely PT

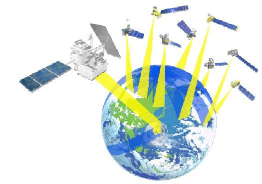
← A priori PDF of PT by region and season

↓

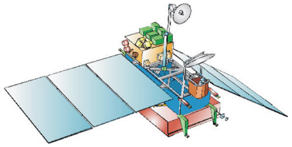
Output the PT and corresponding *R* profile



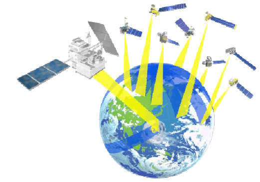
Current Status



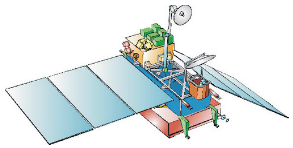
- DF algorithms are available for ideal cases.
- DF algorithms applicable for uniform and relatively light rain: $1 < R < 10$ mm/h.
- If R>10 mm/h, Ka signal may disappear near the surface due to large attenuation.
  - DF algorithm is applicable down to this height.
  - How to extend the DSD information above this height to below it.
- In ice phase regions, DF observation is not enough to estimate 3 parameters (N_0, D_0, density). We need to assume a relationship among them to calculate the snowfall rate.



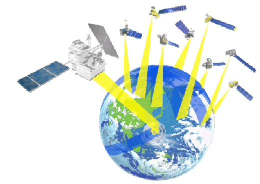
Summary and future work (1/3)



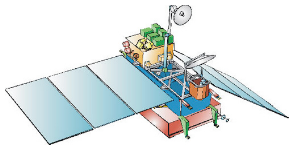
- Major uncertainties (**DSD** and **calibration** (**attenuation** to the first range gate)) in SF algorithm can be reduced with DF algorithms.
  - DF algorithm (RM method) can estimate two DSD parameters at each range bin.
  - DF algorithms may mitigate the issue with unreliable PIA, and unknown attenuation by CLW, H_2O, BB, etc.
    - some attenuation can be estimated if the DSD model is constrained.
    - DFHB method can estimate the attenuation to the first range gate (DSD model with a single parameter is assumed. Needs enough attenuation over a path).
- Combination of single- and double-parameter DSD models is unavoidable.
  - Combination of different algorithms
    - Optimum weights and combination among *Zm*(Ku), *Zm*(Ka), SRT(Ka) and SRT(Ku) depend on region, height, rain rate, etc.



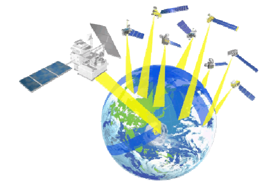
Summary and future work (2/3)



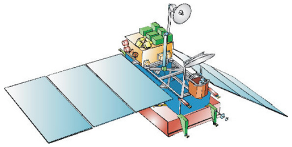
- Even with DPR, we need to assume some profiles.
  - attenuation profile due to WV and Cloud
  - rain profile between the surface and the lowest data point
  - Models and GV measurements are of great value.
- Attenuation correction, DSD parameter retrievals, beam mismatching effect, and NUBF corrections are all entangled.
  - How to disentangle each effect is a challenge.
  - More simulation studies are required to evaluate each effect and to reveal how they are coupled.
  - Denser samples of KaPR (than KuPR or TRMM PR) will provide better information of inhomogeneity, but the correction method is yet to be developed.
- More probabilistic or deterministic constraints from other data or models will help reduce the estimation error.
  - However, use of other data sources makes the validation of the algorithm more difficult. (better to keep at least one algorithm independent of the consensus algorithm.)



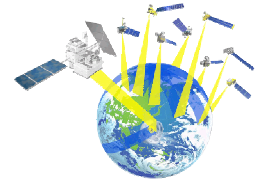
Summary and future work (3/3)

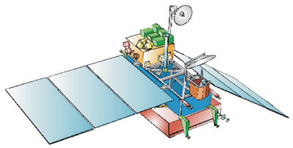


- Evaluation of the error in each piece of available information is necessary.
- We need to agree on how to use and combine all available information (with users and other algorithm developers).
  - continuous or discrete parameter model?
    - rain type classification, ice particle model, etc.
    - to what extent do we adopt Bayesian statistical method?
- We need to evaluate the performance of the algorithms by testing them with simulated data which are created based on
  - airborne data (PR-2, APR-2)
    - realistic data but with many unknown parameters (e.g., clouds)
  - model data
    - all parameters are available but many of them are calculated with unrealistic assumptions
  - purely synthetic data
    - can create any (unrealistic) extreme cases.

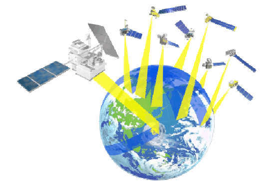


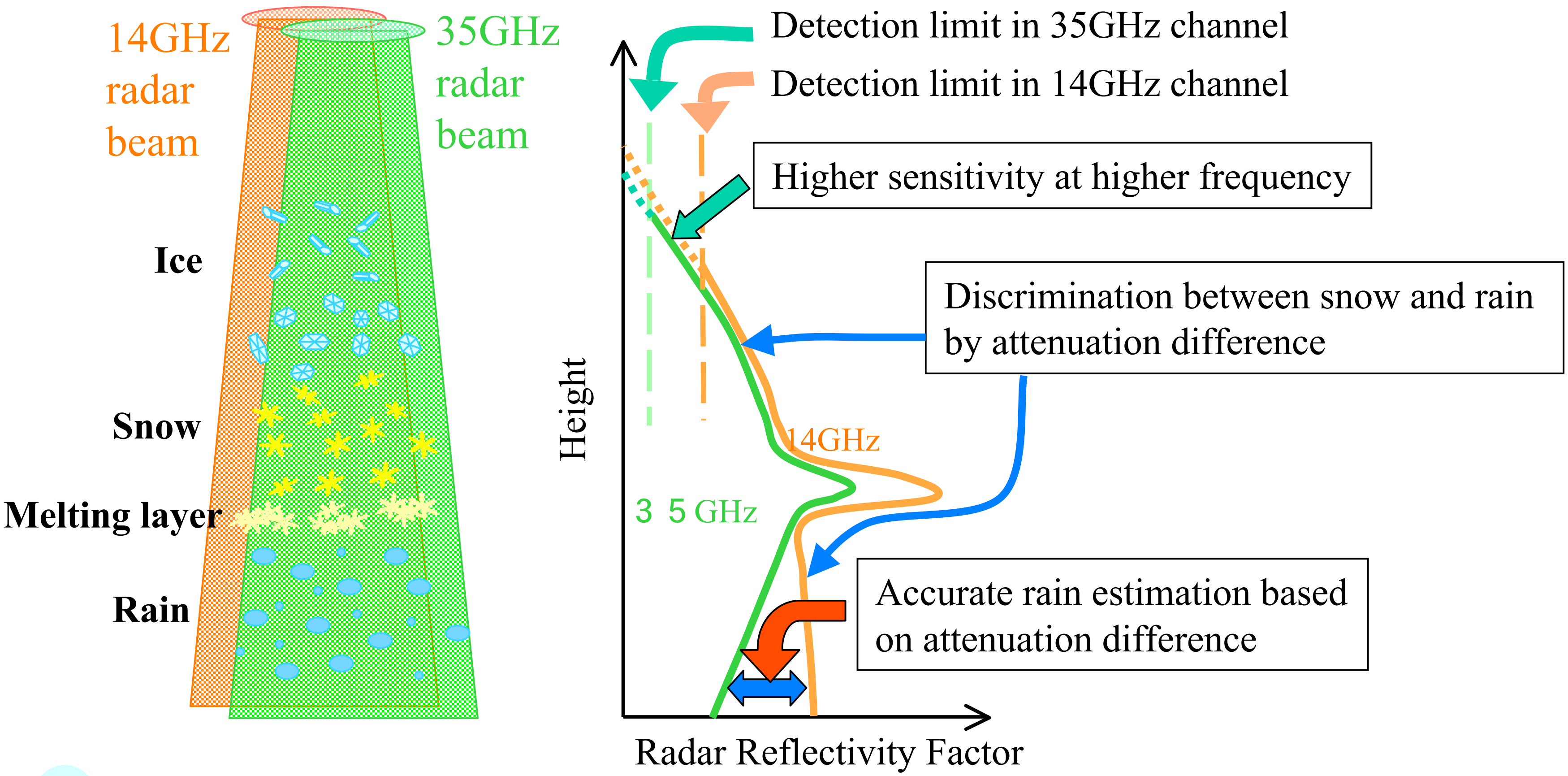
Back-up Slides



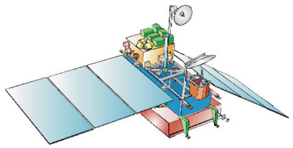


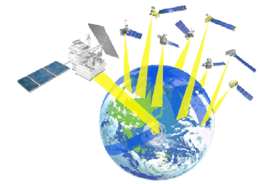
Dual Frequency Precipitation Radar





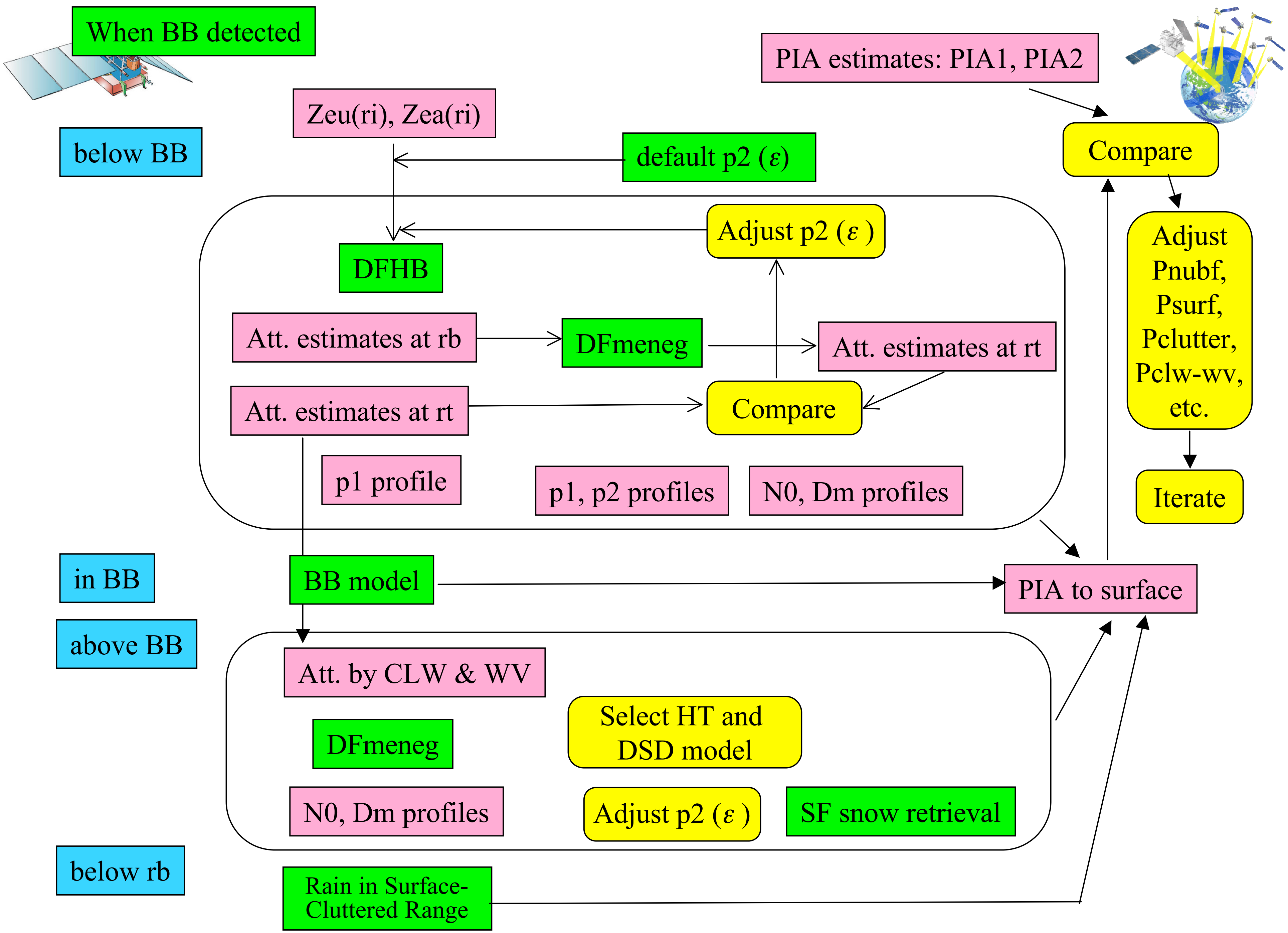
- Measure 3-D structure of rain as TRMM, but with better sensitivity
- Accumulate climatological precipitation data continuously since TRMM
- **Improve estimation accuracy with dual-frequency radar**
  - Identification of hydrometer type
  - Estimation of one or two DSD parameters at each range bin

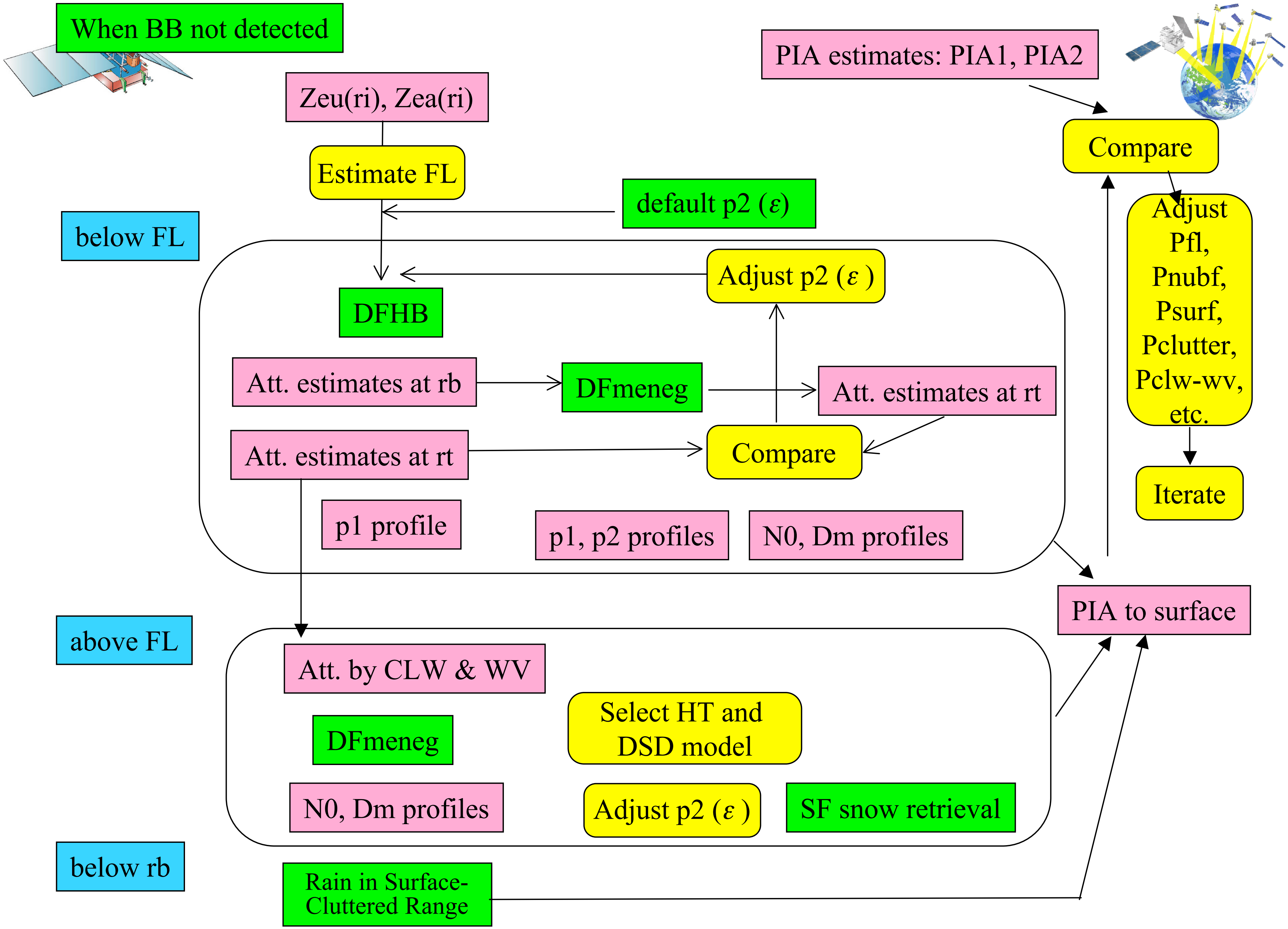




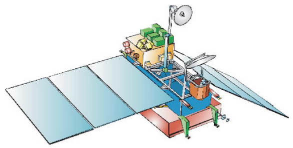
Input and Output data

- Input data: $2(n+1)$ variables
  - $P_{r\mathrm{u}}(r_i)$, $P_{r\mathrm{a}}(r_i)$, $P_{r\mathrm{u}}(r_{\mathrm{surf}})$, $P_{r\mathrm{a}}(r_{\mathrm{surf}})$ (i=1,...,n)
  - or equivalently: $Z_{e\mathrm{u}}(r_{\mathrm{i}})$, $Z_{e\mathrm{a}}(r_i)$, $\sigma^0{}_{\mathrm{u}}$, $\sigma^0{}_{\mathrm{a}}$
- Output data: more than $(n+1)$ variables
  - $R(r_i)$, $\mathrm{PIA_u}$, $\mathrm{PIA_a}$
    - $N_0(r_i)$, $D_{\mathrm{m}}(r_i)$
  - Rain Type
  - Freezing Height
  - Hydrometeor types (transition levels)
  - *R* profile in surface clutter
  - Inhomogeneity
- Ill-posed problem

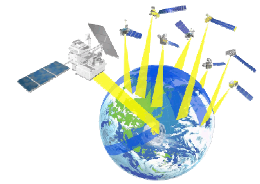

When BB detected
below BB
Zeu(ri), Zea(ri)
default p2 (ε)
PIA estimates: PIA1, PIA2
Compare
Adjust p2 (ε)
DFHB
Att. estimates at rb
DFmeneg
Att. estimates at rt
Att. estimates at rt
Compare
Adjust Pnubf, Psurf, Pclutter, Pclw-wv, etc.
p1 profile
p1, p2 profiles
N0, Dm profiles
Iterate
in BB
BB model
PIA to surface
above BB
Att. by CLW & WV
DFmeneg
Select HT and DSD model
N0, Dm profiles
Adjust p2 (ε)
SF snow retrieval
below rb
Rain in Surface-Cluttered Range

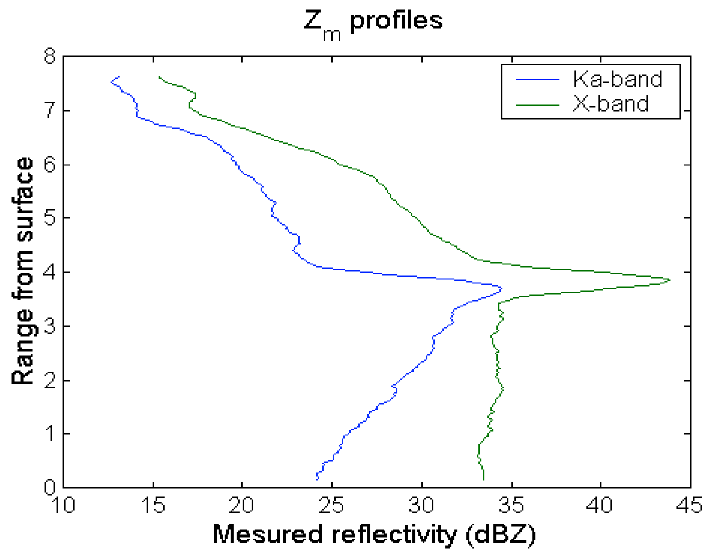


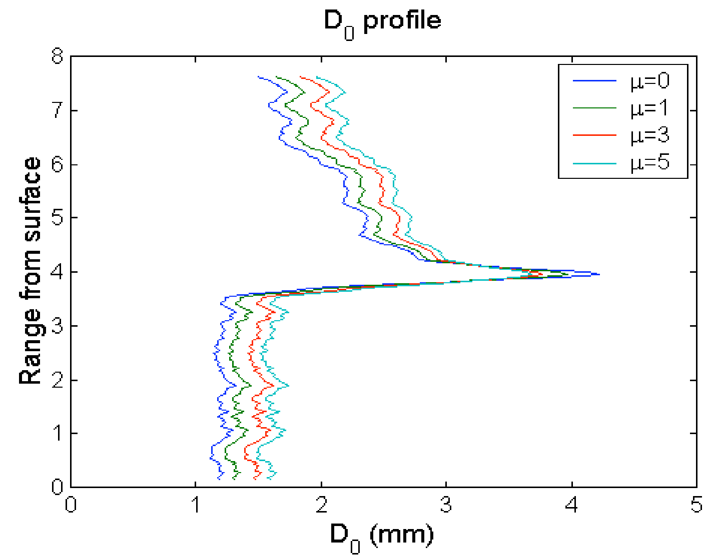
When BB not detected
Zeu(ri), Zea(ri)
Estimate FL
default p2 (ε)
PIA estimates: PIA1, PIA2
Compare
Adjust Pfl, Pnubf, Psurf, Pclutter, Pclw-wv, etc.
Iterate
below FL
DFHB
Adjust p2 (ε)
Att. estimates at rb
DFmeneg
Att. estimates at rt
Att. estimates at rt
Compare
p1 profile
p1, p2 profiles
N0, Dm profiles
PIA to surface
above FL
Att. by CLW & WV
DFmeneg
Select HT and DSD model
N0, Dm profiles
Adjust p2 (ε)
SF snow retrieval
below rb
Rain in Surface-Cluttered Range

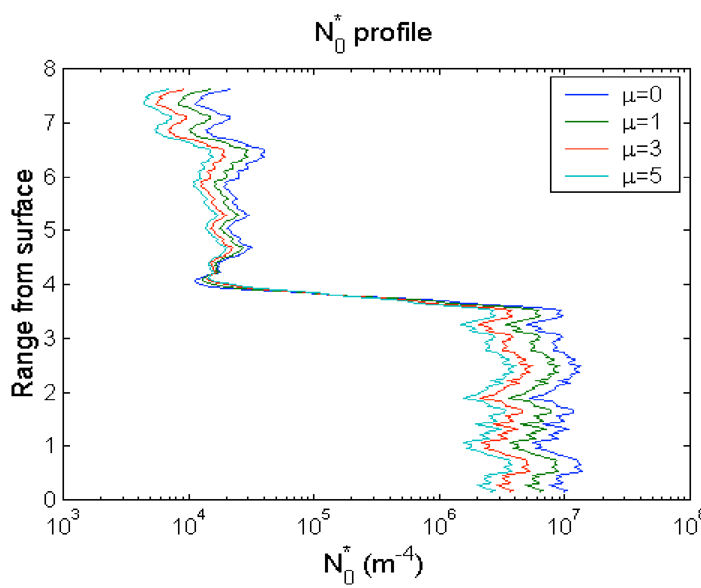


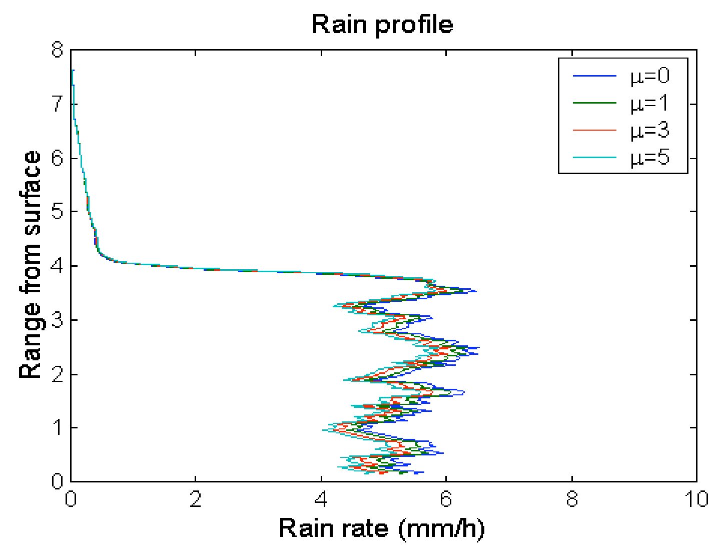
Effect of different μ in R retrieval

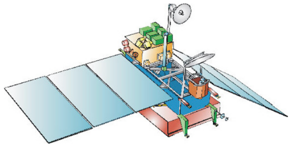


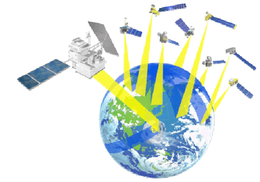






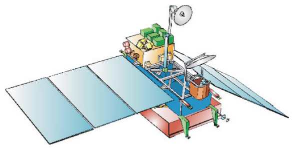




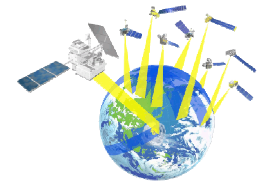


How to detect BB and estimate FL

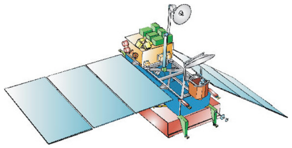
- Apply DFHB in an interval with rain certain
- Find Att. at the top of this interval (rt).
- Use DFmeneg to estimate N_0 and D_m above rt assuming HT is rain.
- DFmeneg will give an unrealistically large D_m in BB. N_0 becomes very small in snow region. --> BB can be detected.
- Use DFmeneg above rt assuming HT is snow or graupel. Compare snow (N_0, D_m) profile with rain (N_0, D_m) profile. Increase rt. Find the best rt above which rain (N_0, D_m) is unrealistic.

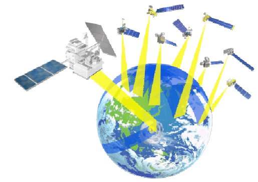


CLW and WV



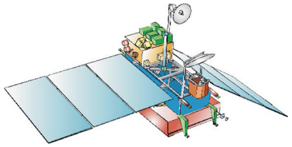
- TRMM 2A25 algorithm gives CLW and WV profiles as functions of *R* at surface.
- It is probably easier to iterate if we can give CLW and WV as function of *R* at just below the FL (rt) or at the cloud bottom height.
- CLW and WV as functions of *R* are based on a numerical storm model.



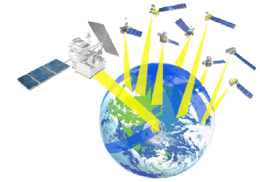


DF algorithm - note

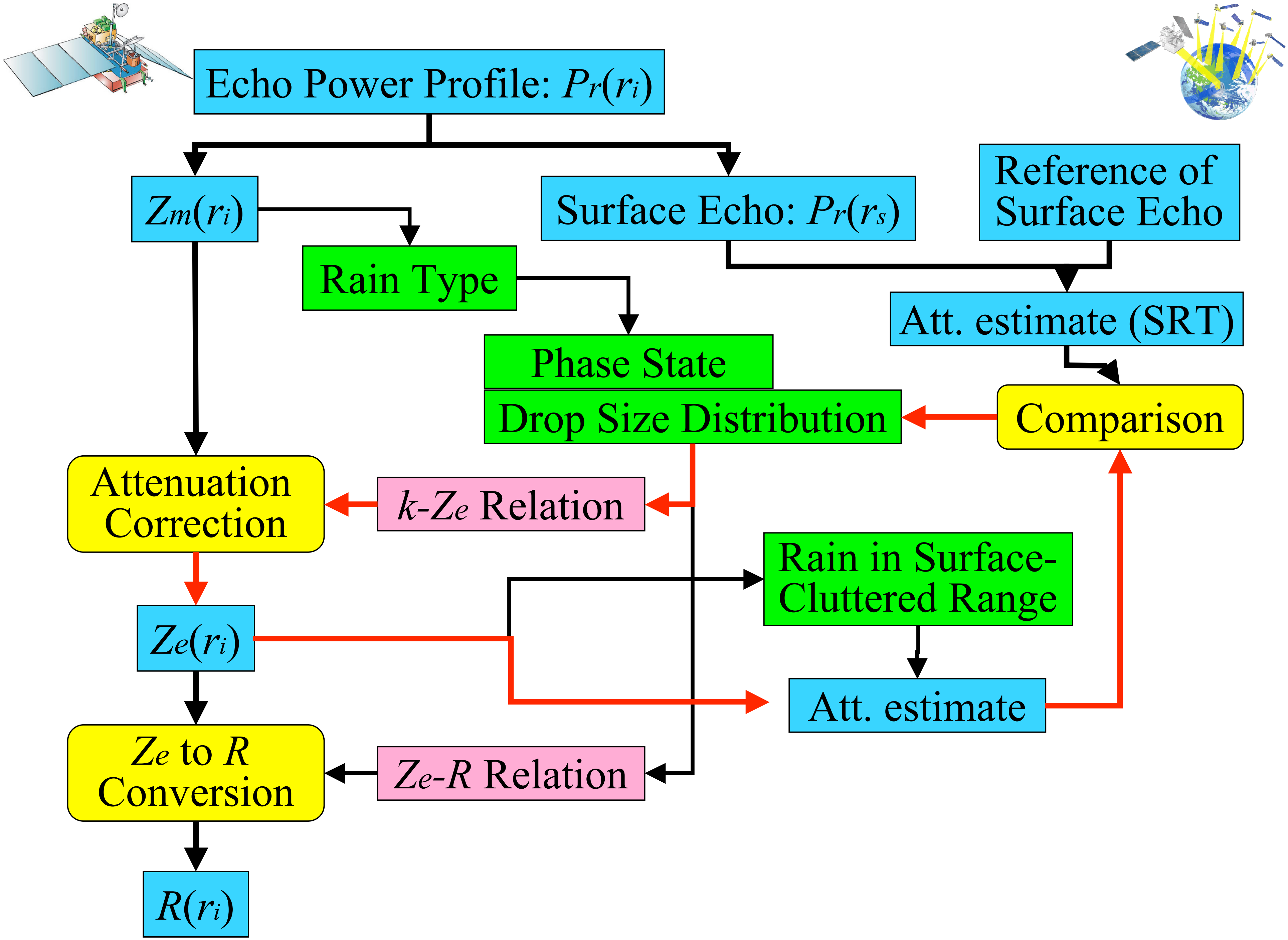
- To minimize the error associated with finite steps in solving the DF rain retrieval equations, it may be better to create profiles of Ze at fine range interval by interpolating the original data.



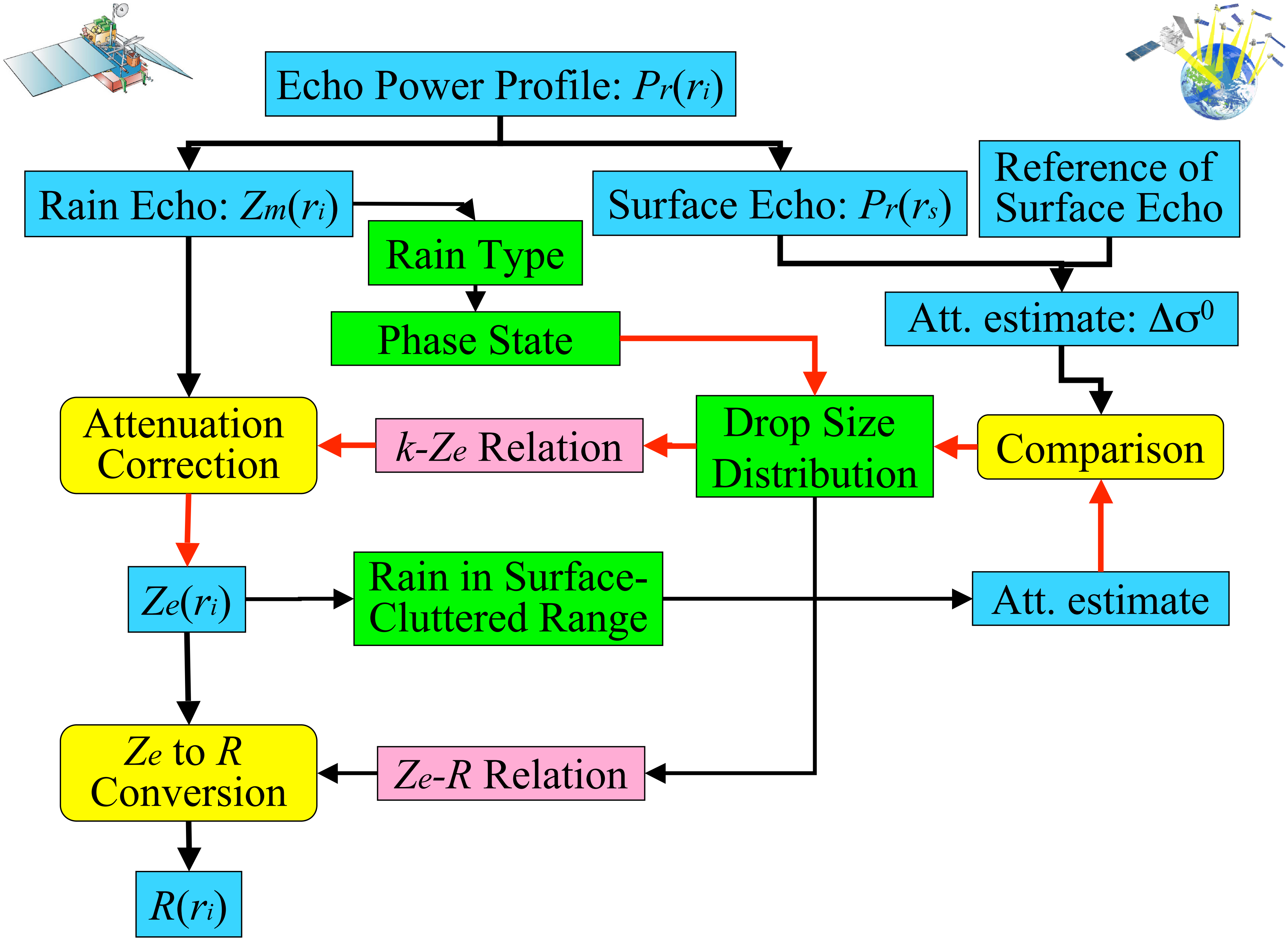
Beam mismatching



- The relative scan angles of each radar are stable.
- JAXA and NASA are worrying about the bias angle between Ka and Ku radars.
- 1km relative offset at incidence angle 8 degrees (near scan edge) will produce the range difference of about 180 m to the Earth's surface. This difference can easily be detected.
- Cross-correlation analysis of rain echoes, in particular echoes from snow at high altitudes, will reveal the offset.
- The issue is whether we can reconstruct a matched pair of Zm profiles from the observed profiles of which the amount of displacement is known.



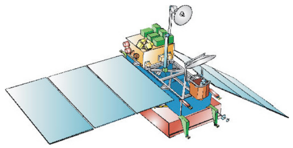
Echo Power Profile: $P_r(r_i)$
$Z_m(r_i)$
Surface Echo: $P_r(r_s)$
Reference of Surface Echo
Rain Type
Att. estimate (SRT)
Phase State
Drop Size Distribution
Comparison
Attenuation Correction
k-Z_e Relation
Rain in Surface-Cluttered Range
$Z_e(r_i)$
Att. estimate
Z_e to R Conversion
Z_e-R Relation
$R(r_i)$



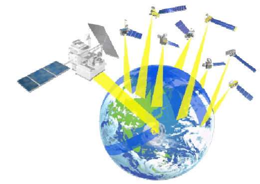
Echo Power Profile: $P_r(r_i)$
Rain Echo: $Z_m(r_i)$
Surface Echo: $P_r(r_s)$
Reference of Surface Echo
Rain Type
Phase State
Att. estimate: $\Delta\sigma^0$
Attenuation Correction
k-Z_e Relation
Drop Size Distribution
Comparison
$Z_e(r_i)$
Rain in Surface-Cluttered Range
Att. estimate
Z_e to R Conversion
Z_e-R Relation
$R(r_i)$

Increase of interest in DF radar algorithms

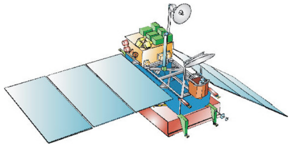
- Necessity of simultaneous measurements of precipitation, clouds, etc. with multiple radars and/or lidars.
  - cloud radar and lidar for cloud and aerosol measurements
  - wind profiler (VHF, P, L) and cloud radar (Ka, W) for precipitation measurements.
  - DF radar (X/Ku and Ka/W) for airborne precipitation measurements. (EDOP, CAPRIS)

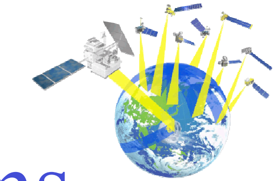


Groups/people interested in DF algorithms for spaceborne radar



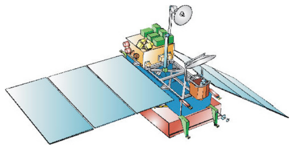
- Japan
  - NICT (Iguchi, Takahashi, et al.)
    - CRL DF radar (X+Ka), (Windprofiler+Ku+W)
  - Nagoya U (Nakamura, et al.)
  - Shimane U (Kozu, et al.)
  - NIED (Iwanami, et al.)
    - Windprofiler+Ka+W
- US
  - NASA/GSFC (Meneghini, et al.)
    - EDOP (X) + Cloud radar (W)
  - JPL (Haddad, Durden, Meagher, et al.)
    - PR2 (Ku + Ka)
  - CSU (Rose, Chandrasekhar)
- Europe



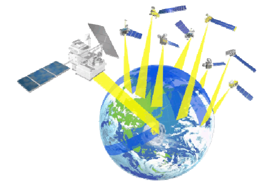


Need for combining different algorithms

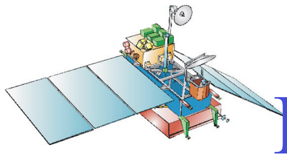
- Depending on the height,
  - the available information and the number of unknowns are different,
  - we need to use different DSD models (single-parameter or dual-parameter model),
  - the validity of assumptions are different,
- We need to combine retrieval algorithms with single- and dual-parameter DSD models.
  - The solutions must be continuous and consistent at the boundaries.
- We need to maximize the use of available information.



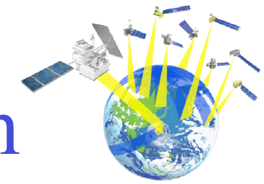
Dual Frequency Algorithms



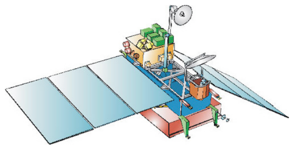
- Difference between attenuation differences at two frequencies over a certain path (DAD-method)
  - *k*-*R* relationship, path-averaged rain rate
  - independent of calibration
  - needs significant attenuation
  - assumes $Z_{e1}(r_1)/Z_{e2}(r_1)=Z_{e1}(r_2)/Z_{e2}(r_2)$
- Two independent measurements at each range bin (Ze-ratio method, RM method)
  - Estimate two DSD parameters at each range bin
    - Rainfall rate, precipitation water content
  - Needs initial conditions (e.g., surface reference)
- Other methods (e.g., DFHB-method)
  - E.g., combination of single frequency methods



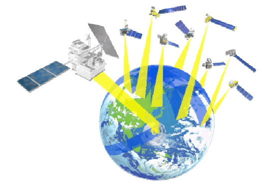
Basic Idea of Meneghini's DF Algorithm



- 2*N* observables (Z_m at 2 freq.) to estimate RR at *N* range gates.
  - If the relations among *Z*, *R* and *k* were constant, *R* would be overdetermined. In fact, *Z*, *R* and *k* are functions of many parameters (DSD, phase, shape, temp., vertical air velocity, non-uniformity, etc.)
- Parameterize DSD with two variables.
  - E.g., N_0 and D_0、N_0^* and D_0
- Estimate these two parameters at each gate.
  - 2*N* estimates from 2*N* observables
- All other parameters are fixed.
  - E.g. shape parameter in DSD, phase, temp, etc.
- Calculate *R* with the estimated parameters.
- Needs 2 initial conditions
  - e.g., 2 PIA's, 2 $\Delta\sigma^0$'s (SRT) , attenuations at the rain top, etc.



Combined H-B (DFHB) Method



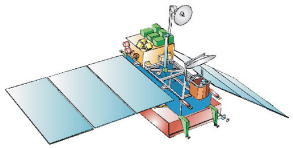
- Hitschfeld-Bordan method applied to both bands of data.
  - **single-parameter DSD model**
    - Assume $k_1 = \alpha_1 Z_{e1}^{\beta_1}, \quad k_2 = \alpha_2 Z_{e2}^{\beta_2} \quad R_1 = a_1 Z_{e1}^{b_1} \quad R_2 = a_2 Z_{e2}^{b_2}$
  - $2N$ data to estimate N+2 unknowns (R, A_{b1}, A_{b2})
- Constraint: RR estimates at two channels must be the same.

$$R_1(r; A_{b1}) = a_1 \frac{Z_{m1}^{b_1}(r)}{[A_{b1}^{\beta_1} - q\beta_1\alpha_1 \int_{r_b}^{r} Z_{m1}^{\beta_1}(s)\, ds]^{b_1/\beta_1}}$$

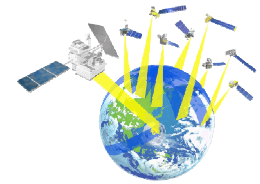
$$R_2(r; A_{b2}) = a_2 \frac{Z_{m2}^{b_2}(r)}{[A_{b2}^{\beta_2} - q\beta_2\alpha_2 \int_{r_b}^{r} Z_{m2}^{\beta_2}(s)\, ds]^{b_2/\beta_2}}$$

  - Minimize $\displaystyle \int \left(\frac{R_1(s; A_{b_1}) - R_2(s; A_{b_2})}{R_1(s; A_{b_1}) + R_2(s; A_{b_2})} \right)^2 ds$

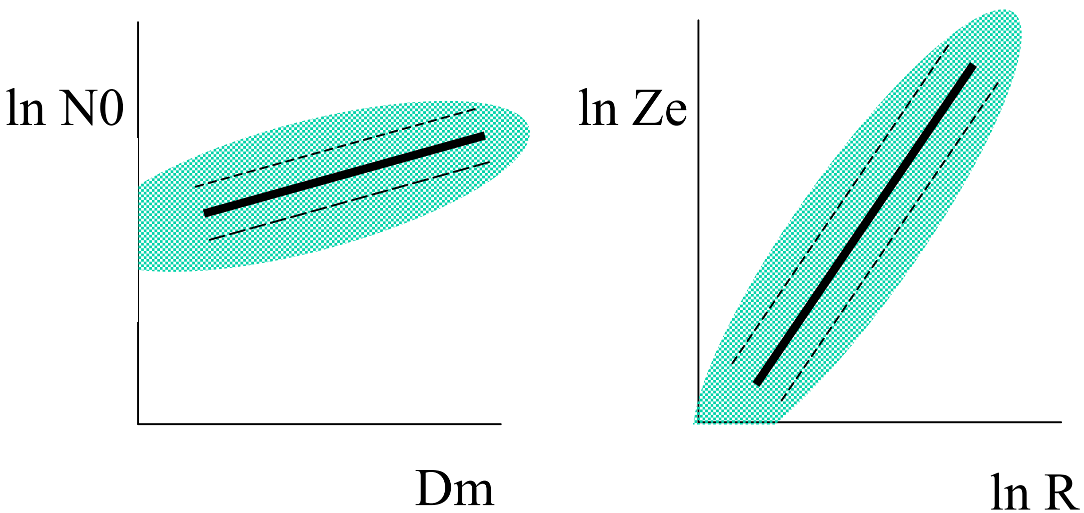
- Can estimate the unknown attenuations (A_{b1}, A_{b2}) to the boundary.
- Initial conditions (e.g., surface reference) not required.
- Applicable to any interval as long as attn. is significant.
- Performance depends on the assumed DSD model.



Issues in DF Algorithms



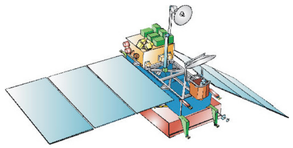
Once a two-parameter DSD model is selected, a Ze-R relation defines a relation between the two parameters (e.g. N0 and Dm).

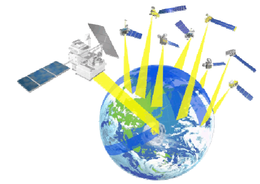


SF algorithms based on the Ze-R (or k-Ze) relation always give a solution in a realistic domain.

DF algorithms (e.g., RM method) without any constraint may give a(n) (unrealistic) solution outside the hatched region.

Some mechanism that limits the solutions within a reasonable bounds should be devised.





Special Concerns in Rain Profiling Algorithms for Spaceborne Radar

- Attenuation correction is essential
  - Attenuation by precipitation is not negligible.
    - In particular, Ka-band radar
    - *k-Z* relation for rain attenuation (H-B solution)
  - Attenuation by CLW and WV is not negligible.
    - **Cloud liquid water: Att(Ka) = 10 * Att(Ku), up to 5 dB**
    - **Water vapor: Att(Ka) = 5 * Att(Ku), up to 1.5 dB near surface**
    - **Oxygen: Att(ka) = 5 * Att(Ku), 0.4 dB near surface**
  - Use of surface reference technique (SRT) helps.
    - But, SR is not always available or reliable
- Type of particles (rain, snow, graupel, etc.) and their physical and electromagnetic properties need to be known (or assumed).
- Inhomogeneity of rain within IFOV
  - Entangled with apparent attenuation, etc.